

Measurement of velocity deficit at the downstream of a 1:10 axial hydrokinetic turbine model

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ABSTRACT

Wake recovery constrains the downstream spacing and density of turbines that can be deployed in turbine farms and limits the amount of energy that can be produced at a hydrokinetic energy site. This study investigates the wake recovery at the downstream of a 1:10 axial flow turbine model using a pulse-to-pulse coherent Acoustic Doppler Profiler (ADP). In addition, turbine inflow and outflow velocities were measured for calculating the thrust on the turbine. The result shows that the depth-averaged longitudinal velocity recovers to 97% of the inflow velocity at 35 turbine diameter (D) downstream of the turbine.

INTRODUCTION

Wake flows downstream of hydrokinetic turbines cause a velocity deficit and an increase in turbulence intensity that increase the structural loading and affect the overall performance of the machines turbines in turbine arrays. As a result, wake flow recovery is a major determinant of turbine spacing and density in hydrokinetic farms and needs to be considered to optimize annual energy production and the cost of energy (Neary et al. 2012). Computational fluid dynamics models used to predict wake flow recovery and optimize turbine spacing at development sites require wake flow measurements for model validation (Bahaj et al. 2007). However, little information is available on wake flow recovery downstream of hydrokinetic turbines. Studies of wake flow characteristics were unable to observe wake flow recovery due to limitations of the test section length (Myers and Bahaj 2006; Maganga et al. 2010). In this study we quantify the velocity deficit downstream of a 1:10 axial flow turbine model using a pulse-to-pulse coherent ADP. Velocity at an inflow and an outflow cross section were also measured to demonstrate the feasibility of using an ADP to calculate the thrust on the turbine. Thrust can be used to develop a thrust coefficient curve for different inflow conditions and turbine blade velocities, and for calculating the bearing size in the drive shaft of the turbine.

MEASUREMENT DETAILS

Measurements were collected in the SAFL Main Channel, which is 2.8 m wide, 1.8 m deep, and 85 m long. The flow rate is monitored using a Massa ultrasonic range sensor mounted upstream of a sharp-crested weir tailgate. As shown in Fig. 1a, a 1:10 scale three-blade axial flow turbine, with a 0.5 m rotor diameter (D), nacelle length of 0.39 m and a hub height of 0.425

m, was mounted to the floor in the center of the channel approximately 40 m (80 diameters) downstream of flow straighteners. The turbine blocked less than 2% of the flow cross-section. Its hub centerline was located at 0.425m from the bed, in a flow depth (h) of 1.16m. For the test case considered, the turbine operates at 90 RPM, which gives an optimal power coefficient value, of 0.48. Velocity was measured using a Sontek pulse coherent acoustic Doppler profiler (PC-ADP) (Sontek 2003). The PC-ADP was mounted downward looking from the SAFL Main Channel data acquisition (DAQ) carriage as shown in Fig. 1a and 1b to collect vertical velocity profile measurements along the centerline plane from upstream to downstream of the turbine at $x/D = -10, -5, -3, -2, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 25, 30$, and 35, with x is the distance from the turbine. Data were collected for 300s at each location with the ADP sampling at 1Hz. For thrust calculation, velocity was measured along the transverse direction at an inflow and an outflow cross-section. Inflow velocity was measured using the ADP moving vessel method at $5D$ upstream of the turbine to ensure the inflow was not affected by deceleration caused by the turbine drag. Five transect measurements were collected and spatially averaged together to obtain the representative velocities along the cross-section. The spatially averaged velocities are assumed to be representative of the cross-section since they have a close agreement (3%) with nine profiles of longitudinal mean velocities collected along the cross-section using the ADP fixed vessel method. The outflow velocities were measured along the transverse direction at a cross section located at $1D$ downstream of the turbine. The location is the closest location to the turbine where the ADCP acoustic beams do not interfere with any parts of the turbine. Seventeen profiles were collected within 0.4m to the right and left of the turbine centerline. Velocities in the unmeasured region, in between the profiles, were interpolated from the measured velocities using the Inverse Distance Weighting method. All ADP data were post processed following the methods provided in Gunawan et al. (2011) and Gunawan et al. (2010).

DISCUSSION OF RESULTS

Fig.2. depicts the vertical velocity profiles of mean longitudinal velocities at various distances upstream and downstream from the turbine. Velocity decreases immediately upstream of the turbine due to the drag from the turbine. For $x/D = -1$, the velocity at a small region just above the hub might be contaminated by the ADP side lobe sound wave that hit the nacelle of the turbine. The velocity recovers gradually at the downstream of the turbine. Fig.3. shows the plots of the depth-averaged (U_d) and local velocity (U_{hub}) at several locations upstream and downstream of the turbine. Both variables are normalized by the mean inflow velocity (U_{inf}). There is a significant decreases, by 44% and 72%, in the near-wake region between $x/D=0$ and 5. The depth-averaged velocity recovers rapidly up to $x/D = 9$, from a value of 56 to 88%. From these point on the recovery rate is slower. U_d recovers to 97% at $x/D = 35$, the most downstream measurement location. The local velocity recovery is initially more accelerated than the depth-averaged velocity up to about $x/D=10$, but rates of recovery past this location are similar and significantly reduced. Neither velocity is fully recovered at $x/D=35$. Contours of longitudinal velocity at $1D$ downstream and $5D$ upstream of the turbine, plotted in Fig. 4., indicate significant decreases immediately downstream of the turbine. On average, the longitudinal velocity decreases by 44% at the energy extraction plane. Thrust (T) and thrust coefficient (C_T) can be calculated using:

$$T = \frac{1}{2}\rho A(U_{in}^2 - U_{out}^2)$$

$$C_T = \frac{T}{\frac{1}{2}\rho A U_{in}^2}$$

to obtain a thrust of 4.6N and a thrust coefficient of 0.2.

CONCLUSIONS

An ADP is a useful instrument for examining wake flow dynamics and recovery in the laboratory. ADP measurements for calculating thrust on the turbine, as demonstrated in this laboratory study, are easily adapted to field scale applications. This study indicates that full recovery of the far-wake does not occur even at 35D downstream of the turbine. This observation may be due to the confinement of the laboratory flume, which prevents the momentum exchange between the wake and free flow field necessary for recovery. Despite this limitation of the laboratory study, it does suggest that turbine arrays will have to be designed to operate in wake fields of upstream turbines. The flow is significantly recovered at downstream distances of 10D to 15D. These distances, therefore, represent the likely practical design spacing for turbine arrays.

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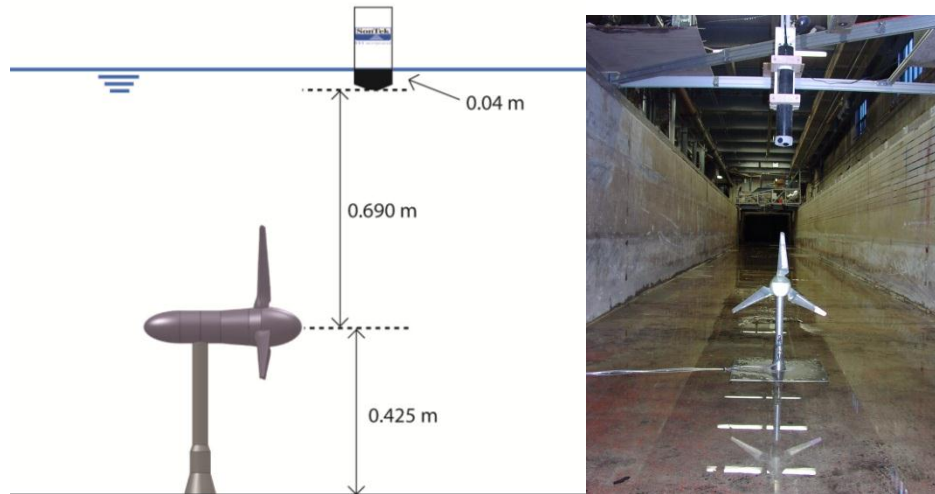


Fig. 1. Diagram of setup for Sontek PC-ADP used for measurements.

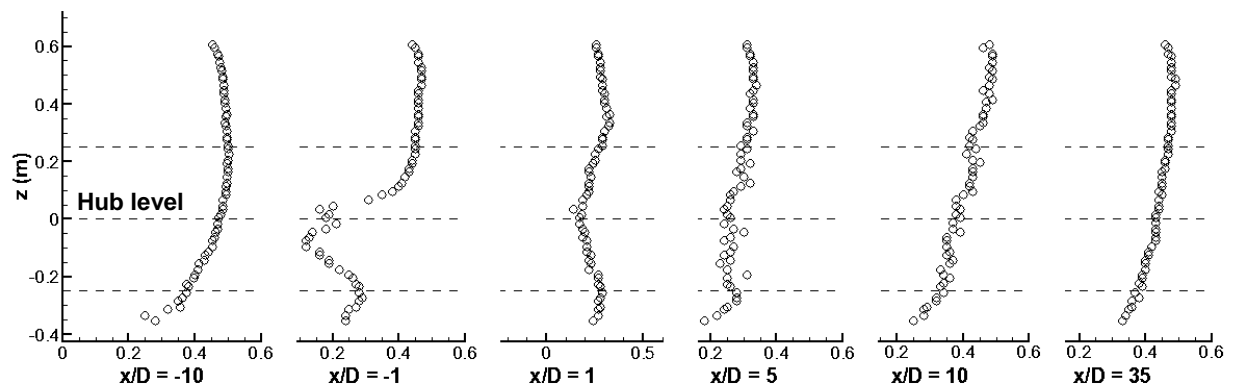


Fig. 2. Vertical profiles of mean longitudinal velocities at various distances upstream and downstream of the turbine.

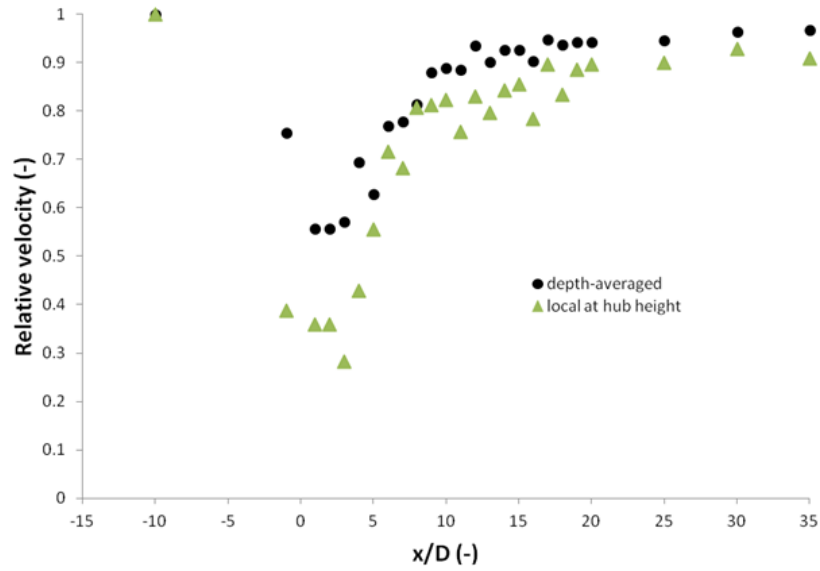


Fig. 3. Relative depth averaged and local hub-height longitudinal velocities.

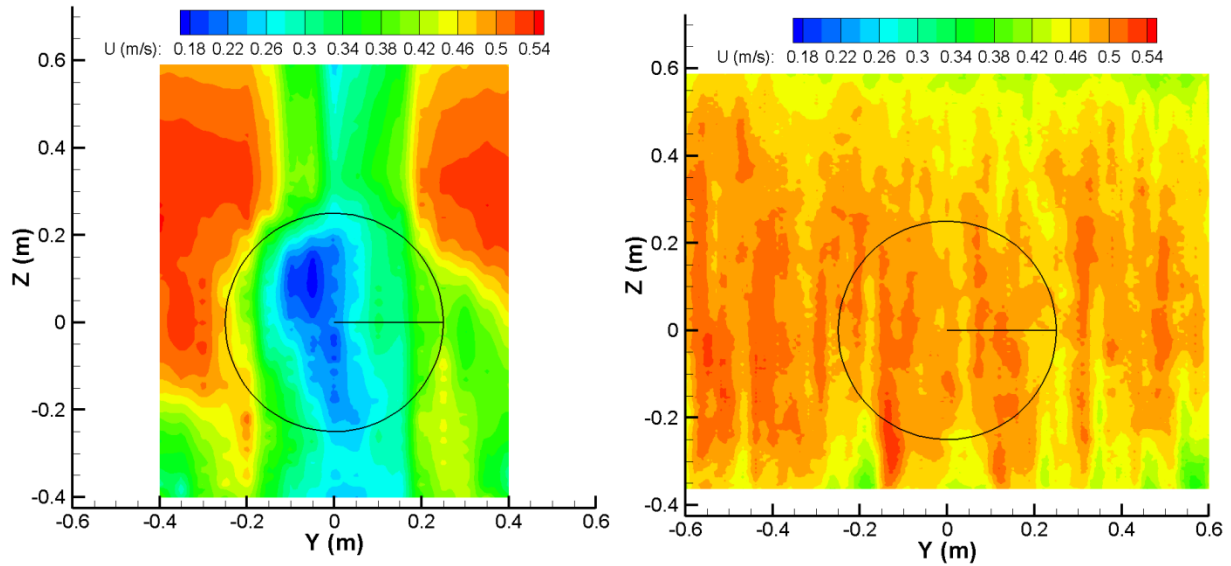


Fig.4. Longitudinal velocity at 1D downstream (a) and 5D upstream (b) of the turbine, circles indicate the location of the turbine rotor.